

# **The Variable Outflow from the Chukchi Shelf to the Arctic Ocean**

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## **LONG-TERM GOALS**

Our long-term research goals are to understand the circulation and physical properties of the high-latitude ocean, both quantitatively and mechanistically, and to do so in a more global context. We also seek to understand the effects of physical processes in the ocean on the ice cover, biology, and chemistry of the marine environment. The variability of that environment is a special focus and concern.

## **OBJECTIVES**

Our objectives are to 1) ascertain the variability of the shelf-basin system as exemplified by the Chukchi Sea-Arctic Ocean couple; 2) identify, and where possible quantify, the important physical mechanisms controlling this system; 3) contribute to the SBI goals by illuminating the mechanisms of shelf-basin exchange; and 4) promote further improvements in the rapidly growing array of models of arctic circulation, hydrographic structures, and variability by providing measurements against which to test the fidelity of these models. Our measurements include moored time series, supplemented by hydrographic and other ship-borne data. Our focus is both on the transformation and outflow from the shelf of Pacific waters that have entered through Bering Strait [*Weingartner et al.*, 2005; *Woodgate et al.*, 2005a; b], and on providing a context in which the SBI process studies can be embedded.

## **APPROACH**

Together with T. Weingartner, UAF we have made moored time series measurements of velocity, temperature, salinity, and ice drift in the northern Chukchi Sea during 2002-2004 in support of SBI Phase 2. Our moorings were sited within the primary throughflows on the northern Chukchi shelf [Barrow Canyon (ca. 80 m depth), the Central Channel (ca. 50 m), and on the north-central shelf downstream of Herald Valley (ca. 70 m and 110 m)]. The moorings included current meters, both fixed-depth and profiling (ADCP), the latter with bottom tracking to measure ice drift, together with temperature/ conductivity recorders. In closely related efforts, R. Pickart, WHOI maintained a

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mesoscale array on the Beaufort slope near 152°W, and J. Swift, SIO provided CTD/rosette sections to support the mooring work. These sections also included ADCP measurements that give detailed spatial information about the velocity field.

To provide a context for the process studies and the overall SBI effort, we are also examining other data sets that uniquely contribute to understanding the modification of the Pacific inflow, to its role and fate in the Arctic Ocean, and to the larger role of arctic shelf-basin interaction in the global ocean.

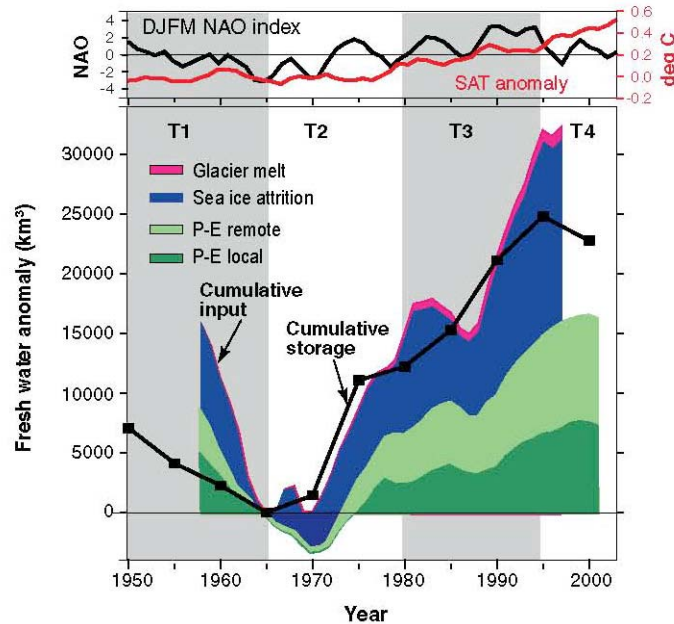
## **WORK COMPLETED**

Data processing has been completed and all moored data have been submitted to JOSS/EOL for archiving, as designated by the SBI program. The data are also archived at our web site (<http://psc.apl.washington.edu/Chukchi.html>).

In our analysis work we have made a considerable effort to synthesize a variety of data to provide a broad perspective on arctic shelf-basin processes [cf., *Swift et al.*, 2005 for an example]. Our analysis efforts under this grant have resulted in seven published papers, along with numerous presentations at national and international meetings. Several of the published results new this year are described below.

## **RESULTS**

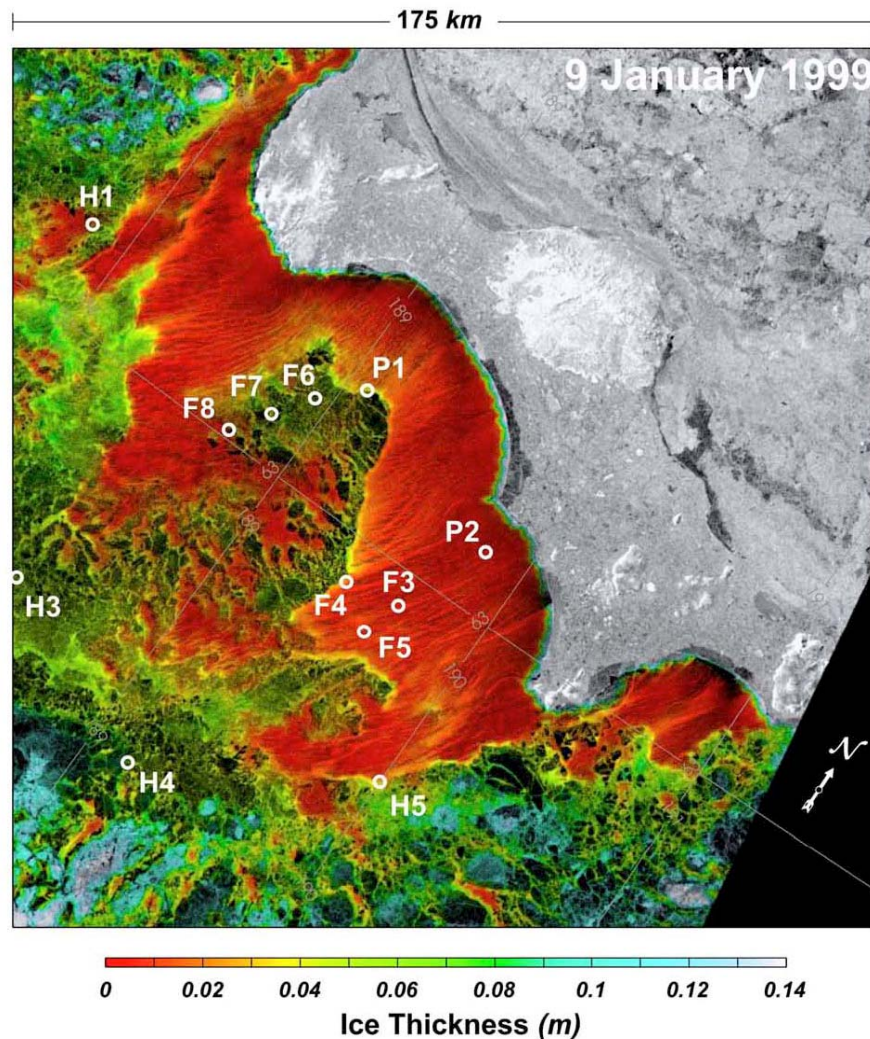
The effects of changes in the processing of freshwater in the Arctic and sub-Arctic are of global importance, and the SBI region is an integral part of this problem set. For example, the inflow of freshwater through Bering Strait is equivalent to about three-fourths of the total runoff into the Arctic Ocean [*Woodgate and Aagaard*, 2005; *Woodgate et al.*, 2006; *Serreze et al.*, in press]. Together with investigators at several other institutions, we have undertaken a synthesis of changes in northern high-latitude freshwater sources and ocean freshwater storage that illustrates the complementary and synoptic temporal pattern and magnitude of these changes over the past 50 years (Figure 1, *Peterson et al.*, 2006). We find that increasing river discharge anomalies and excess net precipitation on the ocean contributed ~20,000 km<sup>3</sup> freshwater to the Arctic Ocean and the high-latitude North Atlantic, from lows in the 1960s to highs in the 1990s. Sea ice attrition provided another ~15,000 km<sup>3</sup>, and glacial melt added ~2,000 km<sup>3</sup>. The sum of anomalous inputs from these freshwater sources matched the amount and rate at which freshwater accumulated in the North Atlantic during much of the period from 1965 through 1995. The changes in freshwater inputs and ocean storage occurred in conjunction with the amplifying North Atlantic Oscillation (NAO) and rising air temperatures. Freshwater may now be accumulating in the Arctic Ocean and will likely be exported southward if and when the NAO enters into a new high phase.



**Figure 1: Comparison of freshwater source and storage anomalies relative to 1965. Black curve is cumulative anomalous freshwater storage in the Nordic Seas and North Atlantic subpolar basins. Colored areas represent cumulative freshwater anomaly contributions from local precipitation minus evaporation (subpolar basins and Nordic Seas - dark green); remote precipitation minus evaporation (Arctic Ocean, Hudson Bay watershed, Canadian archipelago, and runoff – light green); sea ice attrition (blue); and glacier melt (red). Source contributions are stacked to show total freshwater anomaly source input. Figure copyright 2006 by the American Association for the Advancement of Science.**

The annual cycle of freezing and melting of sea ice is of major importance to conditions on the arctic shelves, including the SBI region, and the ensuing shelf conditions also affect the adjacent basins. Much of the ice production has been thought to occur in coastal polynyas, where extremely saline waters may form [Aagaard *et al.*, 1985; Weingartner *et al.*, 2005]. To explore this problem set, we have examined conditions in the St. Lawrence Island polynya on the northern Bering shelf (Figure 2), which feeds the Bering Strait throughflow and downstream Chukchi Sea. Using the records from fourteen year-long instrumented moorings deployed south of St. Lawrence Island, along with oceanographic drifters, we have assessed the circulation over the central Bering shelf and the role of polynyas in forming and disseminating saline waters over the shelf. We have paid particular attention to evaluating the Gawarkiewicz and Chapman [1995] model of eddy production within coastal polynyas. Principal results of our analysis include: 1) The northern central shelf near-surface waters exhibit westward flow carrying low-salinity waters from the Alaskan coast in fall and early winter, with consequences for water mass formation and biological production. 2) Within the St. Lawrence polynya, the freshening effect of winter advection is about half as large as the salting effect of surface brine flux resulting from freezing. 3) Brine production over the Bering shelf occurs primarily offshore, rather than within the polynyas. 4) We find little evidence for the geostrophic flow adjustment predicted by recent polynya models. 5) In contrast to the theoretical prediction that dense water from the polynya is carried offshore by eddies, we find negligible cross-shelf eddy density fluxes within and surrounding the polynya and very low levels of eddy energy that decrease from fall to winter, even though dense water accumulated within the polynya and large cross-shore density gradients develop.

6) It is possible that dense polynya water was advected downstream of our array before appreciable eddy fluxes materialized.



**Figure 2:** Composite SAR and AVHRR image of the St. Lawrence Island polynya on 9 January 1999, adapted from Drucker et al. [2003]. The polynya appears strongly wind-driven, with the winds and waves forcing the frazil ice into the long linear streaks characteristic of a Langmuir circulation. Mooring locations are plotted. SAR image copyright 1999 by the Canadian Space Agency.

## IMPACT/APPLICATIONS

Major goals of the SBI initiative are to understand the physical processes responsible for water mass modification over the arctic shelves and slopes, and for exchanges with the interior ocean, as well as to understand the variability of this system. Our reported project addresses these goals directly. In particular, we are quantifying the large variability found in the Pacific-origin waters that flush the western Arctic shelves, as well as illuminating the origin of this variability. Much of the latter is generated in the Bering Sea [Woodgate et al., 2005a], although the northward-flowing waters may in some years be further modified in the Chukchi, particularly during winter along the Alaskan coast [Weingartner et al., 2005]. The shelf waters are subsequently discharged into the Arctic Ocean, where their seasonal and interannual variability are propagated long distances, in part by long-lived eddies

that drift into the interior [Newton *et al.*, 1974; Manley and Hunkins, 1985], in part by topographically steered boundary currents that rim both the Polar Basin and its major ridge structures [Aagaard, 1989], and in part by other features of the circulation. This propagation leads to variability in regions far from the originating shelves [cf., Swift *et al.*, 1997 and Woodgate *et al.*, 2001 for examples]. An understanding of these effects and processes is vital to realistically modeling the Arctic Ocean and its global connections [Huang and Schmitt, 1993; Wadley and Bigg, 2002; DeBoer and Nof, 2004]].

Our measurements of the time-dependent shelf circulation provide important guidance to investigations of shelf productivity and biochemical cycling. For example, water parcels leaving the northern Chukchi shelf will exhibit substantially different carbon and nutrient loading, depending on their upstream trajectories and the season [Walsh *et al.*, 1997; Woodgate *et al.*, 2005a]. Our work also addresses other prominent issues, including the role of polynyas [Danielson *et al.*, in press]; the flux and processing of freshwater [Woodgate and Aagaard, 2005; Peterson *et al.*, 2006; Woodgate *et al.*, 2006; Aagaard *et al.*, in press; Serreze *et al.*, in press]; mixing over the slope [Woodgate *et al.*, 2005b]; and the needs of a variety of arctic simulations for accurate long-term boundary conditions and observations for verification.

## RELATED PROJECTS

Our work on the northern Chukchi shelf is collaborative with T. Weingartner, UAF; with R. Pickart, WHOI, who is concentrating on the adjacent Beaufort shelf and slope; and with J. Swift, SIO, who has made hydrographic measurements throughout the SBI region. Additionally, we have ongoing collaborations in the region with E. Carmack and F. McLaughlin, IOS.

## REFERENCES

- Aagaard, K., A synthesis of the Arctic Ocean circulation, *Rapp. P.-V. Reun. Cons. Int. Explor. Mer*, 188, 11-22, 1989.
- Aagaard, K., J.H. Swift, and E.C. Carmack, Thermohaline circulation in the arctic mediterranean seas, *J. Geophys. Res.*, 90, 4833-4846, 1985.
- Aagaard, K., T.J. Weingartner, S.L. Danielson, R.A. Woodgate, G.C. Johnson, and T.E. Whitledge, Some controls on flow and salinity in Bering Strait, *Geophys. Res. Lett.*, in press.
- Danielson, S., K. Aagaard, T. Weingartner, S. Martin, P. Winsor, G. Gawarkiewicz, and D. Quadfasel, The St. Lawrence polynya and the Bering shelf circulation: New observations that test the models, *J. Geophys. Res.*, 111, C09023, doi:10.1029/2005JC003268, 2006 [published, refereed]
- DeBoer, A. M., and D. Nof, The exhaust valve of the North Atlantic, *J. Clim.*, 17 (3), 417-422, 2004.
- Gawarkiewicz, G. and D. C. Chapman, A numerical study of dense water formation and transport on a shallow, sloping continental shelf, *J. Geophys. Res.*, 100, 4489-4508, 1995.
- Huang, R. X., and R. W. Schmitt, The Goldsbrough-Stommel circulation of the world ocean, *J. Phys. Oceanogr.*, 23, 1277-1284, 1993.

- Manley, T.O., and K. Hunkins (1985), Mesoscale eddies in the Arctic Ocean, *J. Geophys. Res.*, *90*, 4911-4930.
- Newton, J.L., K. Aagaard, and L.K. Coachman (1974), Baroclinic eddies in the Arctic Ocean, *Deep Sea Res.*, *21*, 707-719, 1974.
- Peterson, B.J., J. McClelland, R. Curry, R.M. Holmes, J.E. Walsh, and K. Aagaard, Trajectory shifts in the arctic and subarctic freshwater cycle, *Science*, *313*, 1061-1066, 2006.
- Serreze, M.C., A.P. Barrett, A.G. Slater, R.A. Woodgate, K. Aagaard, R. Lammers, M. Steele, R. Moritz, M. Meredith, and C.M. Lee, The large-scale freshwater cycle of the Arctic, *J. Geophys. Res.*, in press.
- Swift, J.H., K. Aagaard, L. Timokhov, and Ev. G. Nikiforov, Long-term variability of Arctic Ocean waters: Evidence from a reanalysis of the EWG data set, *J. Geophys. Res.*, *110*, No. C3, C03012, doi:10.1029/2004JC02312, 2005.
- Swift, J.H., E.P. Jones, K. Aagaard, E.C. Carmack, M. Hingston, R.W. Macdonald, F.A. McLaughlin, and R.G. Perkin, Waters of the Makarov and Canada basins, *Deep-Sea Res. Part II*, *44*, 1503-1529, 1997.
- Wadley, M. R., and G. R. Bigg , Impact of flow through the Canadian Archipelago and Bering Strait on the North Atlantic and Arctic circulation: An ocean modelling study, *Quart. J. Royal Met. Soc.*, *128*, 2187-2203, 2002.
- Walsh, J.J., D.A. Dieterle, F.E. Muller-Karger, K. Aagaard, A.T. Roach, T.E. Whitledge, and D. Stockwell, CO<sub>2</sub> cycling in the coastal ocean. II. Seasonal organic loading of the Arctic Ocean from source waters in the Bering Sea, *Continental Shelf Res.*, *17*, 1-36, 1997.
- Weingartner, T., K. Aagaard, R. Woodgate, S. Danielson, Y. Sasaki, and D. Cavalieri, Circulation on the north central Chukchi Sea shelf, *Deep-Sea Res. II*, *52* (24-26), 3150-3174, 2005.
- Woodgate, R.A., and K. Aagaard, Revising the Bering Strait freshwater flux into the Arctic Ocean, *Geophys. Res. Lett.*, *32*, L02602, doi:10.1029/2004GL021747, 2005.
- Woodgate, R.A., K. Aagaard, and T. Weingartner, A year in the physical oceanography of the Chukchi Sea: Moored measurements from autumn 1990-1991, *Deep-Sea Res. II*, *52* (24-26), 3116-3149, 2005a.
- Woodgate, R.A., K. Aagaard, and T.J. Weingartner, Interannual changes in the Bering Strait fluxes of volume, heat and freshwater between 1991 and 2004, *Geophys. Res. Lett.*, *33*, L15609, doi:10.1029/2006GL026931, 2006.
- Woodgate, R.A., K. Aagaard, J.H. Swift, K. Falkner, and W.M. Smethie Jr., Pacific ventilation of the Arctic Ocean's lower halocline by upwelling and diapycnal mixing over the continental margin, *Geophys. Res. Lett.*, *32*, No. 18, L18609, doi:10.1029/2005GL023999, 2005b.
- Woodgate, R.A., K. Aagaard, R.D. Muench, J. Gunn, G. Björk, B. Rudels., A.T. Roach, and U. Schauer, The Arctic Ocean boundary current along the Eurasian slope and the adjacent Lomonosov



Ridge: Water mass properties, transports and transformations from moored instruments, *Deep-Sea Res. I*, 48, 1757-1792, 2001.

## PUBLICATIONS

Aagaard, K., T.J. Weingartner, S.L. Danielson, R.A. Woodgate, G.C. Johnson, and T.E. Whitledge, Some controls on flow and salinity in Bering Strait, *Geophys. Res. Lett.* [in press, refereed]

Danielson, S., K. Aagaard, T. Weingartner, S. Martin, P. Winsor, G. Gawarkiewicz, and D. Quadfasel, The St. Lawrence polynya and the Bering shelf circulation: New observations that test the models, *J. Geophys. Res.*, 111, C09023, doi:10.1029/2005JC003268, 2006 [published, refereed]

Peterson, B.J., J. McClelland, R. Curry, R.M. Holmes, J.E. Walsh, and K. Aagaard, Trajectory shifts in the arctic and subarctic freshwater cycle, *Science*, 313, 1061-1066, 2006 [published, refereed]

Swift, J.H., K. Aagaard, L. Timokhov, and Ev. G. Nikiforov, Long-term variability of Arctic Ocean waters: Evidence from a reanalysis of the EWG data set, *J. Geophys. Res.*, 110, No. C3, C03012, doi:10.1029/2004JC02312, 2005 [published, refereed]

Weingartner, T., K. Aagaard, R. Woodgate, S. Danielson, Y. Sasaki, and D. Cavalieri, Circulation on the north central Chukchi Sea shelf, *Deep-Sea Res. II*, 52 (24-26), 3150-3174, 2005 [published, refereed]

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